OPTICAL ELEMENT, OPTICAL DEFLECTION ELEMENT,

OPTICAL MULTIPLEXING ELEMENT, AND SCANNING APPARATUS

5 BACKGROUND OF THE INVENTION

Field of the Invention

The present invention is related to an optical element for emitting an incident light beam in a desirable direction, an optical deflection element for emitting a plurality of light
10 beams having different incidence angles or different wavelengths from each other in different directions, and an optical multiplexing element for optically multiplexing a plurality of light beams having different incidence angles in the same direction. Further, the present invention is related
15 to a scanning apparatus with employment of such an optical deflection element.

Description of a Related Art

Conventionally, as an optical element or an optical
20 deflection element, passive elements such as a prism, a diffraction grating, a concave lens and so on have been utilized. Further, very recently, as an optical deflection element, active elements such as a diffraction grating using an acoust-optic effect and a galvano scanner have been employed.
25 In such a diffraction grating using the acoust-optic

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effect, by propagating a compression wave (for instance, an ultrasonic wave) through a medium such as glass, a refractive index is changed periodically, so that a light beam is emitted in different directions. In a galvano scanner, by vibrating

5 a mirror by using a resonant head, a light beam is emitted in different directions.

However, since the passive elements such as the prism, the diffraction grating, and the concave lens have a small deflection angle at which a light beam is emitted from the

10 passive element, a long optical path is necessarily required so as to separate the incident light beam into a plurality of light beams corresponding to incidence angles or wavelengths. Therefore, in order that the light beams having different incidence angles or different wavelengths are deflected in a

15 wide range, a dimension of such a passive element itself must be increased, and also the entire optical apparatus must be made large so as to secure the long optical path. On the other hand, in the active elements such as the diffraction grating using the acoust-optic effect and the galvano scanner,

20 although light can be deflected in a wide range, cost of the active element itself is expensive, and also the active element owns a slow response to the input signals.

Very recently, specific crystal (namely, photonic crystal) having a different optical characteristic from that

25 of the conventional optical crystal has been effectively

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developed. The photonic crystal owns a crystal structure in which, within a first medium, a second medium having a different refractive index from that of the first medium is arranged at an interval corresponding to a wavelength of light. The

5 photonic crystal owns a refractive index distribution which is changed periodically, and shows such a phenomenon (namely, superprism effect) in which refraction directions of light beams having slightly different incidence angles or wavelengths from each other are largely changed. The optical

10 characteristics shown by the photonic crystal are described in detail, for example, in "Superprism phenomenon in photonic crystals" written by H. Kosaka et al., Physical Review B Vol. 58, No. 16, October 15, 1998, and in Japanese Laid-open Patent Application JP-A-2000-66002.

15   Currently, various optical elements with employment of such photonic crystal as manufacturing materials thereof have been proposed. For example, Japanese Laid-open Patent Application JP-A-2000-56146 discloses such a self-waveguide circuit provided with photonic crystal on a major portion of

20 a substrate so as to propagate a light beam within the substrate in the self-waveguide manner to separate the propagated light beam into a desirable number of light beams. Also, Japanese Laid-open Patent Application JP-A-11-271541 discloses such a wavelength separating circuit having the photonic crystal

25 interposed between two claddings as materials so as to separate

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a light beam in correspondence with wavelengths of the components.

However, those conventional techniques disclosed in the above-mentioned documents are directed to the optical separating operations of the light beams. Therefore, those conventional optical elements/circuits cannot be utilized as, for instance, an optical deflection element for deflecting a plurality of light beams having different incidence angles or different wavelengths in different directions. As described above, no one could succeed in developing of optical elements, optical deflection elements, nor optical multiplexing elements which employ the photonic crystal as manufacturing materials thereof.

SUMMARY OF THE INVENTION

The present invention has been made to solve the above-explained problems. Therefore, a first object of the present invention is to provide an optical element for directing a light beam having a specific wavelength to a desirable direction by changing a propagation direction of the light beam in a wide range, without increasing an element size of the optical element, and furthermore, without increasing manufacturing cost thereof.

Also, a second object of the present invention is to provide an optical deflection element for deflecting light

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beams having different incidence angles or different
wavelengths toward different emergence angles in a wide range,
without increasing an element size of the optical deflection
element, and furthermore, without increasing manufacturing

5   cost thereof.

Furthermore, a third object of the present invention is
to provide an optical multiplexing element for multiplexing
light beams having different incidence angles with each other
and emitting in the same direction, without increasing an

10   element size of the optical multiplexing element, and
furthermore, without increasing manufacturing cost thereof.

In addition, a fourth object of the present invention is
to provide a scanning apparatus for scanning a light beam in
a wide range at a high speed by causing a slight change in the

15   incidence angle or wavelength, without increasing a size of
the apparatus, and furthermore, without increasing
manufacturing cost thereof.

To achieve the above-described objects, an optical
element according to the present invention, comprises:

20   photonic crystal having a refractive index which changes
periodically depending on a location of the photonic crystal;
wherein: an angle defined between a first end face and a second
end face of the optical element is determined in such a manner
that a light beam incident upon the first end face at a

25   predetermined incidence angle and having a predetermined

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wavelength is emitted from the second end face in a desirable direction.

In the optical element, the photonic crystal may be provided between a first normal optical medium and a second normal optical medium.

Also, an optical deflection element according the present invention comprises: photonic crystal having a refractive index which changes periodically depending on a location of the photonic crystal; wherein: the optical deflecting element has a first end face and a second end face; and a shape of the second end face of the optical deflection element is determined in such a manner that a plurality of light beams incident upon the first end face at different incidence angles and having the same wavelength are emitted from the second end face in different directions corresponding to the incidence angles.

Alternatively, the shape of the second end face of the optical deflection element may be determined in such a manner that a plurality of light beams incident upon the first end face at the same incidence angle and having different wavelengths are emitted from the second end face in different directions corresponding to the wavelengths.

In the optical deflection element, the photonic crystal may be provided between a first normal optical medium and the second normal optical medium.

Also, an optical multiplexing element according to the

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present invention comprises: photonic crystal having a
refractive index which changes periodically depending on a
location of the photonic crystal; wherein: a shape of a first
end face of the optical multiplexing element is determined in

5   such a manner that a plurality of light beams incident upon
the first end face of the optical multiplexing element at
different incidence angles are optically multiplexed with each
other along the same direction at a second end face of the
optical multiplexing element.

10   In the optical multiplexing element, the photonic crystal
may be provided between a first normal optical medium and a
second normal optical medium.

Furthermore, a scanning apparatus according to a first
aspect of the present invention comprises: an optical

15   deflection element including photonic crystal having a
refractive index which changes periodically depending on a
location of the photonic crystal, the optical deflection
element having a first end face and a second end face, a shape
of the second surface of the optical deflection element being

20   determined in such a manner that a plurality of light beams
incident upon the first end face at different incidence angles
and having the same wavelength are emitted from the second end
face in different directions corresponding to the incidence
angles; a light source for outputting a light beam having a

25   constant wavelength toward the optical deflection element; and

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a resonant head for vibrating the optical deflection element, whereby a light beam deflected by the optical deflecting element is scanned with respect to an object.

On the other hand, a scanning apparatus according to a second aspect of the present invention comprises: an optical deflection element including photonic crystal having a refractive index which changes periodically depending on a location of the photonic crystal, the optical deflection element having a first end face and a second end face, a shape of the second surface of the optical deflection element is determined in such a manner that a plurality of light beams incident upon the first end face at the same incidence angle and having different wavelengths are emitted from the second end face in different directions corresponding to the wavelengths; and a light source for changing a wavelength of a light beam to be output toward the optical deflection element, whereby a light beam deflected by the optical deflecting element is scanned with respect to an object.

In the scanning apparatus, the photonic crystal may be provided between a first normal optical medium and a second normal optical medium.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a plan view showing a shape of an optical element according to one embodiment of the present invention;

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Fig. 2 is a diagram illustratively showing an example of photonic crystal employed as a material of the optical element as shown in Fig. 1;

Fig. 3 represents a photonic band diagram in such a case

5 where a light beam is propagated through the photonic crystal as shown in Fig. 2 in parallel to the plane of the drawing, which light beam has a plane of polarization parallel to the plane of the drawing;

Fig. 4 is a diagram illustratively showing a first

10 Brillouin zone of the photonic crystal as shown in Fig. 2 which is sliced at a specific normalized frequency;

Fig. 5 is a diagram for explaining a method of drawing a wave vector of a light beam propagated through the photonic crystal and a propagation direction of the light beam based

15 upon a wave vector of the light beam which is incident upon a first end face as shown in Fig. 1;

Fig. 6 is a diagram for explaining a method of drawing an angle "ϕ" defined between the first end face and a second end face as shown in Fig. 1;

20 Fig. 7 is a plan view representing a shape of an optical deflection element according to a first embodiment of the present invention;

Fig. 8 is a diagram for explaining a separation characteristic of light at the first end face as shown in Fig.

25 7;

Fig. 9 is a diagram schematically representing a structure of a scanning apparatus with employment of the optical deflection element in Fig. 7;

Fig. 10 is a plan view representing a shape of an optical deflection element according to a second embodiment of the present invention;

Fig. 11 is a diagram for explaining an separation characteristic of light at the first end face as shown in Fig. 9;

Fig. 12 is a diagram schematically representing a structure of a scanning apparatus with employment of the optical deflection element in Fig. 9;

Fig. 13 is a plan view indicating a shape of an optical deflection element according to a third embodiment of the present invention;

Fig. 14 is a plan view representing a shape of an optical deflection element according to a fourth embodiment of the present invention; and

Fig. 15 is a plan view representing a shape of an optical multiplexing element according to one embodiment of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to drawings, various preferred embodiments of the present invention will be described in detail. It

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should be understood that the same reference numerals will be employed as those for indicating the same structural elements, and therefore, explanations thereof are omitted. It should also be noted that the below-mentioned various numeral values

5 employed in the respective embodiments correspond to typical values for the sake of simplification, and the present invention may be applied to other values by considering the technical scope of the present invention.

Fig. 1 is a plan view showing a shape of an optical element

10 according to one embodiment of the present invention. It should be understood that in the embodiment, an "emergence angle" is referred to as such an angle that is defined between an incident normal on the optical element 10 and a direction in which a light beam is emitted from the optical element 10.

15 The optical element 10 corresponds to a passive element which is used for emitting an incident light beam in a desirable direction. The optical element 10 employs photonic crystal as shown in Fig. 2 as material.

The photonic crystal as shown in Fig. 2 is formed from

20 such a structure. That is, a large number of circular holes 20 are formed in a silicon (Si) substrate 21 periodically (with predetermined intervals) by a two-dimensional triangular lattice arrangement. Those circular holes 20 are filled with air. Due to such a structure, a refractive index of the optical

25 element 10 is changed periodically (cyclically or alternately).

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In the embodiment, while an effective refractive index of the silicon substrate is set to 3.065, a wavelength of an objective light beam which is propagated in a vacuum atmosphere is equal to, for example, 1.55μm, a radius "R" of the circular hole is

5   selected to be 0.387μm, and also a pitch "A" of the circular holes is selected to be 0.93μm.

The photonic crystal as shown in Fig. 2 is fabricated in such a manner that, for instance, after resist is formed on the silicon substrate except for potions where the circular

10   holes are formed, the resultant substrate is treated by a dry etching process having a superior perpendicularity.

It should also be noted that any other media (for example, glass, dielectric material, and polymer) different than the above-described air may be filled into the circular holes 20,

15   and also a medium having a refractive index which is larger than that of silicon may be filled into the circular holes 20. Alternatively, the arrangement of the medium employed in the photonic crystal is not limited to such a two-dimensional triangular lattice arrangement as shown in Fig. 2, but may be

20   realized by a two-dimensional periodic arrangement such as a two-dimensional square-shaped lattice arrangement, a three-dimensional periodic arrangement, and so on. The alternative idea may be similarly applied to the below-mentioned various embodiments.

25   Since a light beam propagated through photonic crystal

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is influenced by a multiple scattering phenomenon caused by the periodic structure of the photonic crystal, a propagation characteristic of the propagated light beam can be explained with reference to such a photonic band diagram which is similar

5   to a band diagram of an electron in a semiconductor. For example, in the case where light is propagated through the photonic crystal as shown in Fig. 2 in parallel to the drawing plane, which light beam has a plane of polarization parallel to the drawing plane, such a photonic band diagram as shown

10   in Fig. 3 is obtained. Such a photonic band diagram gives a relationship between a wave vector in a reciprocal lattice space and a normalized frequency $\Omega = \omega A/(2 \pi c)$. It should be noted that "ω" represents an angular frequency of light and "c" represents a light velocity in a vacuum atmosphere.

15   In Fig. 3, there is shown a photonic band diagram formed by way of the reduced zone scheme. Also, it should be understood that symbols "Γ", "M", "K" given to an abscissa in Fig. 3 indicate specific wave vectors in a first Brillouin zone as shown in Fig. 4.

20   While considering such an example that a wavelength of light of interest is selected to be 1.55μm (normalized frequency $\Omega = 0.6$), a description will now be made of such a method of determining an angle "ϕ" defined between a first end face 11 and a second end face 12 of the photonic crystal

25   as shown in Fig. 1.

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Fig. 5 is a diagram for explaining a method of drawing a wave vector of a light beam propagated through the photonic crystal 10 and a propagation direction of the light beam based upon a wave vector of the light beam which is incident upon

5   a first end face as shown in Fig. 1.

In Fig. 5, there are represented both a constant-frequency dispersion surface Σ_1 in the air, and another constant-frequency dispersion surface Σ_2 in the photonic crystal. It should also be understood that in Fig. 5, the

10 k_x-axis is made coincident with a tangential direction on the first end face 11, and the k_y-axis is made coincident with a normal direction on the first end face 11. The geometrical relationship may be similarly applied to the below-explained geometrical relationship as shown in Fig. 6.

15   In Fig. 5, such a vector k_1 that a point Γ is set as a starting point and another point P_1 on the constant-frequency dispersion surface Σ_1 is set as an end point gives such a wave vector that the coordinates of the point P_1 is employed as a component thereof. Also, an outward-directed normal vector

20 V_1 at the point P_1 on the constant-frequency dispersion surface Σ_1 gives such a direction along which a light beam having a wave vector k_1 is propagated in the air. Similarly, such a vector k_2 that a point Γ is set as a starting point and another point P_2 on the constant-frequency dispersion surface Σ_2 is set

25 as an end point gives such a wave vector that the coordinate

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of the point P_2 is employed as a component thereof. Also, a normal vector V_2 at the point P_2 on the constant-frequency dispersion surface Σ_2 gives such a direction in which light of a wave vector k_2 is propagated in the photonic crystal in

5   Fig. 2. It should also be noted that the direction of the normal vector V_2 is employed as follows: A symbol of $\partial\omega/\partial k$ becomes positive.

On a boundary surface between two different media, tangent components of wave vectors to the boundary surface are

10   saved. As a consequence, in Fig. 5, k_x component of the wave vector is conserved.

The k_x component of the wave vector k_1 is equal to the k_x-coordinate of an intersection point between the k_x-axis and a perpendicular line (namely, Snell line) S_1 which is

15   perpendicularly drawn from the point P_1 to the k_x-axis. As a result, such a vector k_2 that a point Γ is set as a starting point whereas a intersection point P_2 between the constant-frequency dispersion surface Σ_2 and the Snell line S_1 is set as an end point gives such a wave vector of light

20   which is propagated through the photonic crystal in Fig. 2. Then, an angle θ_2 defined between a normal vector V_2 at the point P_2 on the constant-frequency dispersion surface Σ_2 and the k_y-axis gives a refractive angle of such a light beam which is incident upon the first end face 11 at an incidence angle

25   θ_1. The light beam of the wave vector k_2 is propagated at the

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angle θ_2 in the photonic crystal.

Fig. 6 is a diagram for explaining a method of drawing an angle ϕ defined between the first end face 11 and the second end face 12 as shown in Fig. 1.

5   In such a case where the light beam which is propagated through the optical element 10 is emitted from the second end face 12 at an emergence angle θ_4, such a vector k_3 that the point Γ is set as a starting point and the point P_3 on the constant-frequency dispersion surface Σ_1 is set as an end point

10   gives a wave vector of a light bean which is emitted from the second end face 12 at an emergence angle θ_4. Then, a normal vector V_3 at the point P_3 on the constant-frequency dispersion surface Σ_1 gives such a direction in which the light emitted from the second end face 12 is propagated in the air.

15   Also, with respect to the second end face 12, a tangential component of a wave vector is conserved. Therefor, a broken line S_2 passing through two points, which are the end point P_2 of the wave vector k_2 and the end point P_3 of the wave vector k_3, gives a Snell line located perpendicularly to the second

20   end face 12. As a consequence, such a straight line Ξ passing through the point Γ and perpendicular to the Snell line S_2 indicates the tangential direction on the second end face 12, and also, an angle defined between the straight line Ξ and the k_x-axis gives an angle ϕ, which is defined between the first

25   end face 11 and the second end face 12.

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The angle ϕ defined between the first end face 11 and the second end face 12 can be set with a high degree of freedom as far as both the direction in which the light is propagated through the optical element 10 and the direction in which the

5   light is emitted from the optical element 10 are located in the same side to the second end face 12. As a consequence, according to the embodiment, while the propagation direction of the light beam having a particular wavelength is largely changed in the wide range, the light can be derived in the

10 desirable direction without increasing the element size of the optical element and the manufacturing cost thereof.

Fig. 7 is a plan view indicating a shape of an optical deflection element 30 according to a first embodiment of the present invention.

15 It should be understood in the first embodiment that an "emergence angle" is referred to as such an angle defined between an incident normal on the optical deflection element and a direction of a light beam which is emitted from the optical deflection element. The angle definition may be similarly

20 applied to the below-mentioned various embodiments related to the optical deflection element.

An optical deflection element 30 corresponds to such a passive element to be used for emitting light beams having different incidence angles to different emission directions.

25 The optical deflection element 30 is made of such photonic

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crystal as shown in Fig. 2.

While considering such a case where a wavelength of an objective light beam is selected to be 1.55μm and a range of an incidence angle of the light beam is defined from -6.9

5 degrees to -4.3 degrees, a description will now be made of a method of determining a shape of the second end face 32 of the optical deflection element 30.

Fig. 8 is a diagram representing an optical separating characteristic of a light beam at a first end face 31 of the

10 optical deflection element 30. It should also be noted in Fig. 8 that k_x-axis is made coincident with a tangential direction on the first end face 31, and also, k_y-axis is made coincident with a normal direction on the first end face 31.

In Fig. 8, a vector k_{11} indicates a wave vector of a light

15 beam which is incident upon the first end face 31 at an incidence angle θ_{11}, whereas another vector k_{12} indicates a wave vector of a light beam which is incident upon the first end face 31 at an incidence angle θ_{12}, the incidence angle θ_{12} is larger than the above-mentioned incidence angle θ_{11}. Similar to Fig. 5,

20 such a vector V_{11} is given, which is made coincident with a direction in which the light beam of the wave vector k_{11} is propagated through the optical deflection element 30, whereas such a vector V_{12} is given, which is made coincident with a direction in which the light of the wave vector k_{12} is propagated

25 through the optical deflection element 30.

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As shown in Fig. 8, in a concave portion of a constant-frequency dispersion surface Σ_2, a normal direction at a position of incidence is largely changed owing to a slight change in the incidence angle, and thus, a propagation

5   direction of the light beam is largely changed. As a consequence, as shown in Fig. 7, by changing the incidence angle to the first end face 31 slightly, the propagation direction of the light beam in the optical deflection element 30 is largely changed. Concretely speaking, at the first end face

10   31, such incident light beam having an incidence angle θ_I = -4.3 degrees is refracted at a maximum refractive angle θ_P = 57 degrees, whereas such incident light beam having an incidence angle θ_I = -6.9 degrees is refracted at a minimum refractive angle θ_P = 21 degrees. Those light beams are

15   propagated through the optical deflection element 30, while being collimated, and then, reach different positions on the second end face 32.

In the first embodiment, an angle, which is defined between the tangential direction on the first end face 31 and

20   a tangential direction on the second end face 32 at an arrival point of each propagation light beam, is determined in such a manner that the respective propagation light beams propagated through the optical deflection element 30 are emitted from the second end face 32 in different directions

25   from each other. Concretely speaking, an angle ϕ_0 is set to

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a maximum value of 59 degrees where the angle ϕ_0 is defined

between the tangential direction on the first end face 31 and

a tangential direction on the second end face 32 at an arrival

point of such a propagation light beam having a refractive angle

5   θ_P = 57 degrees. Also, an angle ϕ_0 is set to a minimum value

of −65 degrees where the angle ϕ_0 is defined between the

tangential direction on the first end face 31 and a tangential

direction on the second end face 32 at an arrival point of such

a propagation light beam having a refractive angle θ_P = 21

10   degrees. By determining the shape of the second end face 32

in such a manner, such light beams which are incident upon the

first end face 31 at an incidence angle from −6.9 degrees to

−4.3 degrees are deflected at the second end face 32 in

different directions at an emergence angle in such a wide range

15   from −83.3 degrees to +70.3 degrees. As a result, according

to the embodiment, the incident light beams having the

different incidence angles can be deflected in the different

directions over the wide range, while the optical deflection

element is not made large, but also the manufacturing cost

20   thereof is not increased.

As shown in Fig. 9, by combining the optical deflection

element 30, a resonant head 81, a monochromatic laser

oscillator 82, a motor 83 for driving the resonant head 81,

and a motor drive unit 84 for controlling operations of the

25   motor 83, such a scanning apparatus (for example, scanner) 80

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for scanning a light beam onto an object may be constituted. In this case, the scanning apparatus 80 can carry out laser light scanning operation in a high speed and a wide range by causing a slight angle change of a light beam generated from

5   the monochromatic laser oscillator 82 for outputting a laser light beam having a constant wavelength, while the entire scanning apparatus 80 is not made large.

Fig. 10 is a plan view indicating a shape of an optical deflection element 40 according to a second embodiment of the

10   present invention. An optical deflection element 40 corresponds to such a passive element capable of emitting light beams having different wavelengths in different emission directions. The optical deflection element 40 is made of such photonic crystal as indicated in Fig. 2.

15   While considering such a case where a wavelength range of an objective light beam is selected to be from 1.39μm to 1.41μm and an incidence angle of the light beam is set to be -6.0 degrees, a description will now be made of a method of determining a shape of a second end face 42 of the optical

20   deflection element 40. Such a wavelength range of the light beam corresponds to a range of a normalized frequency Ω from 0.66 to 0.669.

Fig. 11 is a diagram representing a separation characteristic of light at a first end face 41 of the optical

25   deflection element 40. In Fig. 11, a constant-frequency

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dispersion surface in the photonic crystal, in which a range

of the normalized frequency Ω is set to be from 0.657 to 0.669,

is drawn with a frequency interval of 1.8%. It should also

be noted in Fig. 11 that k_x-axis is made coincident with a

5   tangential direction on the first end face 41, and also, k_y-axis

is made coincident with a normal direction on the first end

face 41.

As indicated in Fig. 11, the shape of the constant-

frequency dispersion surface denoted by the optical deflection

10   element 40 is changed corresponding to the normalized

frequency Ω. As a result, when a wavelength (normalized

frequency) of such a light beam is changed, which light beam

is incident upon the first end face 41 at a constant incidence

angle, a propagation direction of the light beam in the optical

15   deflection element 40 is largely changed. For instance, when

the normalized frequency Ω is changed from 0.669 to 0.657,

a vector which gives the propagation direction of the light

beam in the optical deflection element 40 is changed from V_{21}

into V_{22}. As a result, as shown in Fig. 10, for instance, such

20   a light beam having a normalized frequency $\Omega = 0.669$ is

refracted at a maximum refractive index $\theta_P = 69$ degrees at the

first end face 41, whereas such a light beam having a normalized

frequency $\Omega = 0.657$ is refracted at a minimum refractive index

$\theta_P = -50$ degrees at the first end face 41. Those light beams

25   are propagated through the optical deflection element 40,

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while being collimated, and then, reach different positions on the second end face 42.

In the second embodiment, an angle defined between the tangential direction on the first end face 41 and a tangential

5   direction on the second end face 42 at an arrival point of each of the propagation light beams is determined in such a manner that the respective propagation light beams propagated through the optical deflection element 40 are emitted from the second end face 42 in the different directions from each other.

10   Concretely speaking, an angle ϕ_0 is set to a maximum value of 53 degrees where the angle ϕ_0 is defined between the tangential direction on the first end face 41 and a tangential direction on the second end face 42 at an arrival point of such a propagation light beam having a refractive angle $\theta_p = 69$ degrees.

15   Also, an angle ϕ_0 is set to a minimum value of −69 degrees where the angle ϕ_0 is defined between the tangential direction on the first end face 41 and a tangential direction on the second end face 42 at an arrival point of such a propagation light beam having a refractive angle $\theta_p = -50$ degrees. By determining

20   the shape of the second end face 42 in such a manner, a light beam, which is incident upon the first end face 41 at the normalized frequency Ω of a range from 0.657 to 0.669, is deflected from the second end face 42 in different directions at an emergence angle in such a wide range from +59.3 degrees

25   to −89.4 degrees. As a result, according to the second

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embodiment, the incident light beams having different wavelengths can be deflected in different directions in the wide range, while the optical deflection element is not made large, but also the manufacturing cost thereof is not

5   increased.

As shown in Fig. 12, by combining the optical deflection element 40 of the second embodiment, a tunable laser oscillator 91 and a laser control unit 92 for controlling operations of the tunable laser oscillator 91, such a scanning apparatus (for

10   example, scanner) 90 may be constituted by which a light beam is scanned onto an object. In the scanning apparatus 90, the laser light beam scanning operation can be carried out in a high speed and a wide range by causing a slight wavelength change, while the entire scanning apparatus 90 is not made

15   large.

In the foregoing description, the optical deflection element employs only the photonic crystal as the manufacturing material. Alternatively, according to the present invention, the optical deflection element may have such a structure in

20   which photonic crystal is interposed between two sets of normal optical media. In the alternative case, the radius of the constant-frequency dispersion surface Σ_1 as shown in Fig. 8 and 11 may be replaced by such a value obtained by multiplying the radius by a refractive index of the normal optical media.

25   More specifically, in the alternative case, as shown in Fig.

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13 or 14, the optical deflection element 50 or 60 may be constituted by employing a material formed in such a manner that the photonic crystal is made only in a part of the normal optical medium (for example, a silicon substrate).

5   In the optical deflection element 50 as shown in Fig. 13, a shape of a second boundary surface 55 of the optical deflection element 50 is determined based upon a drawing method similar to that of Fig. 6 in such a manner that a plurality of light beams having the same wavelength, which are incident

10   upon a first boundary surface 54 between a normal optical medium 51 and the photonic crystal 53 at different incidence angles, are emitted in different directions from the second boundary surface 55 between another normal optical medium 52 and the photonic crystal 53.

15   On the other hand, in the optical deflection element 60 as shown in Fig. 14, a shape of a second boundary surface 65 of the optical deflection element 60 is determined based upon a drawing method similar to that of Fig. 6 in such a manner that a plurality of light beams having different wavelengths,

20   which are incident upon a first boundary surface 64 between a normal optical medium 61 and the photonic crystal 63 at the same incidence angles, are emitted in different directions from the second boundary surface 65 between another normal optical medium 62 and the photonic crystal 63.

25   In those cases, a portion of the normal optical medium

may be merely patterned in the form of the photonic crystal structure, and also the end face treatments of the optical deflection element 30 in the first embodiment or the optical deflection element 40 in the second embodiment are no longer

5   required. As a consequence, the manufacturing steps of those optical deflection elements can be simplified.

It should also be noted that in order to determine the shapes of the second boundary surfaces 55 and 65, the following refractive indexes may be preferably considered, namely, a

10   refractive index between air and the normal optical medium 51 and 52, or a refractive index between air and the normal optical medium 61 and 62. In this case, a refractive angle of a light beam at a light emission end can be made small, and thus, a reflection loss occurred at a boundary surface between air and

15   a normal optical medium may be reduced.

Fig. 15 is a plan view indicating a shape of an optical multiplexing element according to one embodiment of the present invention.

In the above-explained optical deflection elements,

20   owing to the symmetrical characteristic of the constant-frequency dispersion surfaces which characteristic is given by the photonic crystal in Fig. 2, the optical path can be traced in the reverse direction, namely from the light emission side to the light incident side. An optical multiplexing element

25   70 corresponds to a passive element applying such a symmetrical

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characteristic of the photonic crystal as shown in Fig. 2. The optical multiplexing element 70 is used to optically multiplex a plurality of light beams having different incidence angles so as to emit the multiplexed light beam in one direction.

5   A shape of a first end face 71 of the optical multiplexing element 70 is determined based upon a drawing method similar to that as shown in Fig. 6. That is, an angle defined between a tangential direction on the first end face 71 at each position of incidence and a tangential direction on a second end face

10   72 is determined in such a manner that the respective incident light beams L_1 to L_{11}, which are incident upon the first end face 71 at different positions, may be optically multiplexed with each other to produce an emergent light beam L at the second end face 72.

15   As a consequence, according to the embodiment, a plurality of light beams (for instance, monochromatic laser light beams) having the same wavelength and different incidence angles can be optically multiplexed with each other in a high speed in the same direction, and a light beam having

20   a higher strength can be produced, while the optical multiplexing element itself is not made large, but also the manufacturing cost thereof is not increased.

         In the embodiment, the optical multiplexing operation in which a plurality of light beams having the same wavelength

25   and different incidence angles are multiplexed with each other

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is described. Alternatively, an angle defined between the tangential direction on the first end face 71 at each position of incidence and the tangential direction on the second end face 72 may be determined in such a manner that respective

5   incident light beams having different wavelengths, which are incident upon the first end face 71 from different positions, may be optically multiplexed with each other along the same direction at the second end face 72. Also, in the alternative case, a plurality of light beams having different wavelengths

10   can be optically multiplexed with each other in a high speed along the same direction, while the optical multiplexing element itself is not made large, but also the manufacturing cost thereof is not increased. Also, such an optical multiplexing element may be used as, for example, a wavelength

15   mixer used in a wavelength division multiplexing communication field.

As previously described in detailed, according to the present invention, an optical element can be provided which largely changes the propagation direction of a light beam

20   having a specific wavelength in a wide range, and derives the light beam in the desirable direction, without increasing the element size of the optical element and the manufacturing cost thereof.

Also, according to the present invention, an optical

25   deflection element can be provided which deflects incident

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light beams having different incidence angles or different wavelengths at different emergence angles in a wide range, without increasing the element size of the optical deflection element and the manufacturing cost thereof.

5   Furthermore, according to the present invention, an optical multiplexing element can be provided which optically multiplexes a plurality of incident light beams having different incidence angles with each other along the same direction, without increasing the element size of the optical multiplexing element and the manufacturing cost thereof.

10   In addition, according to the present invention, a scanning apparatus can be provided which scans a light beam in a high speed and a wide range by causing a slight angle change of a incidence angle or a wavelength, without increasing the size of the apparatus and the manufacturing cost thereof.

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